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The Use of Vitreous Enamel Coatings to Improve Bonding and Reduce Corrosion in Concrete Reinforcing Steel

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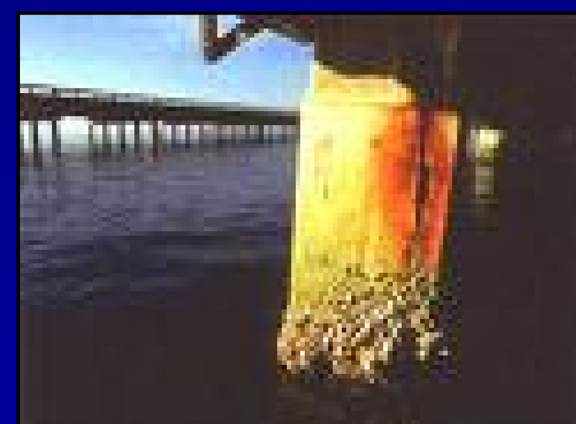
Overview

- Corrosion of Reinforcing Steel in Concrete
- Strategies to Prevent Corrosion
- Alkali-resistant Vitreous Enamel Testing and Results
- Ongoing Demonstration Work at CCAD
- Summary

Problem of Corrosion of Reinforcing Steel in Concrete

- Deterioration of reinforced concrete structures directly effects military readiness.
- Corrosion problems are typically related to docks, bulkheads, retaining walls and mooring structures
- U.S. has 276 inland locks, 1,914 deep water ports and 1,812 ports on inland waterways
- Estimated cost for infrastructure repair is $30M annually



Failure of Concrete with Mild Steel Reinforcement is Due to Corrosion of the Steel

- The major cause of failure in reinforced concrete is the corrosion of the reinforcing steel whether it is rebar or steel fiber
- The rusting of iron embedded in the concrete increases the volume and cracks the concrete apart
- All normal reinforced concrete (cast-in-place and precast) may have a short service life due to corrosion

Concrete Composition

Cement Reactions Set Conditions

Tricalcium silicate + Water--->
Calcium silicate hydrate + Calcium hydroxide + heat

2 Ca3SiO5 + 7 H2O ---> 3 CaO.2SiO2.4H2O + 3 Ca(OH)2 + 173.6kJ

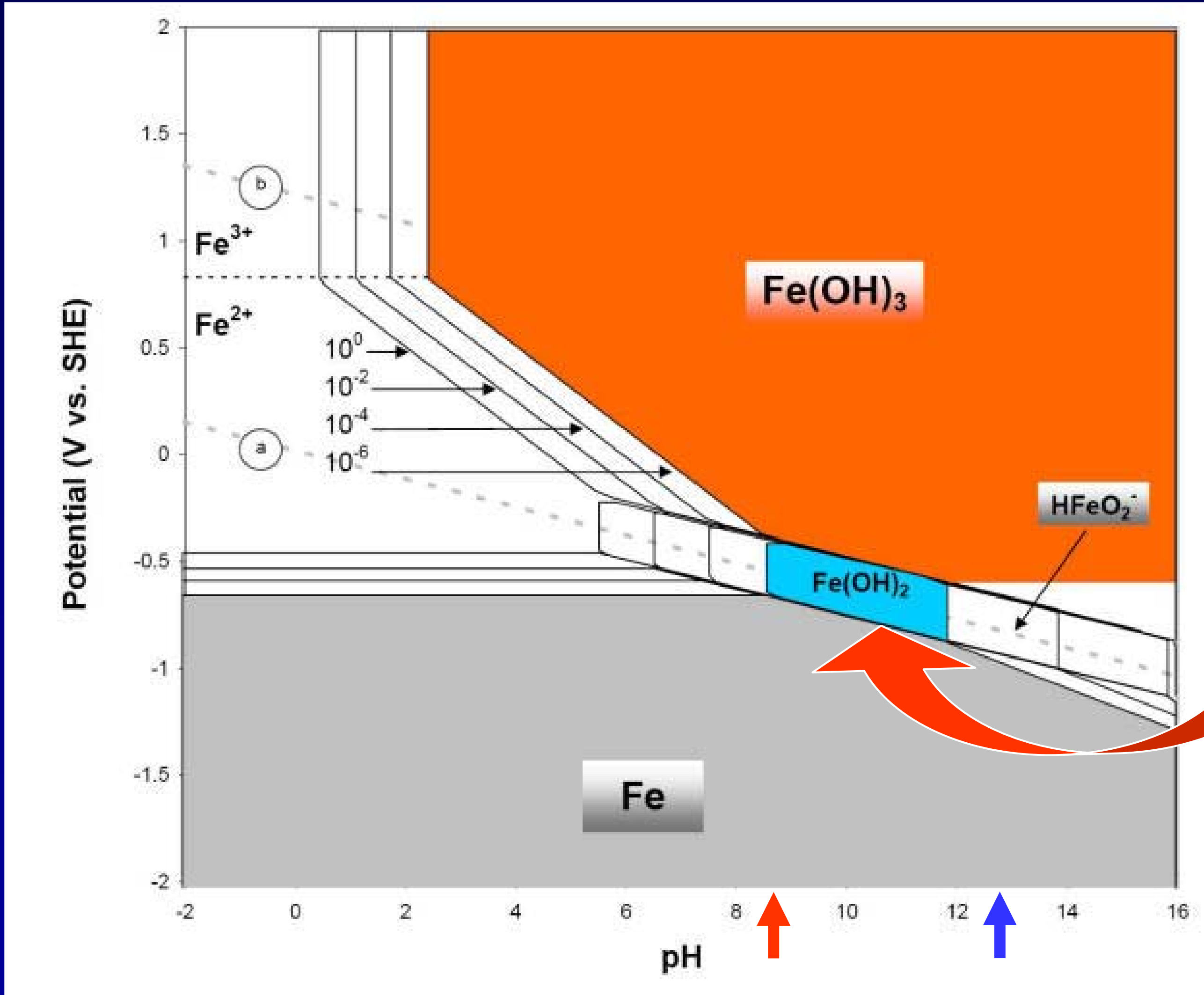
Dicalcium silicate + Water--->

Calcium silicate hydrate + Calcium hydroxide + heat

2 Ca2SiO4 + 5 H2O---> 3 CaO.2SiO2.4H2O + Ca(OH)2 + 58.6 kJ

Initial pH in fresh paste is 12.5 to 13

Formation of Fe Passive Layer



Stable to pH 9

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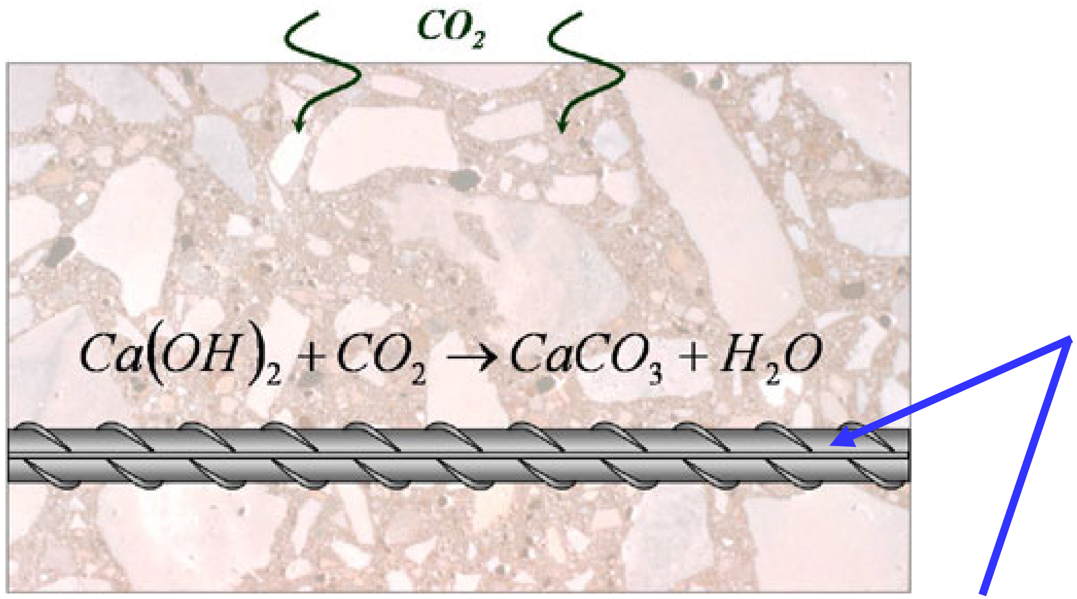
Reduction in pH in Concrete

Pozzolanic Reactions

And

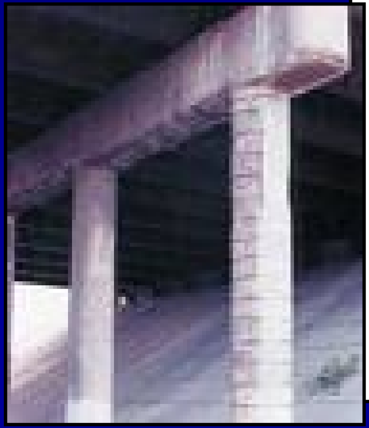
Carbonation

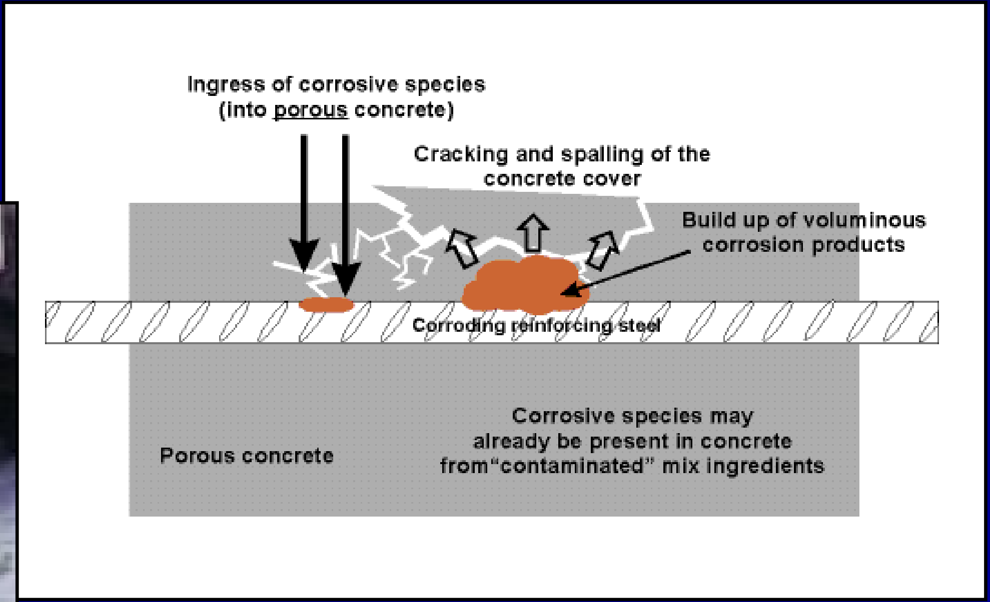


pH drops from ~13 to ~9

Why Reinforcement Steel in Concrete Corrodes

- All chemical changes that occur after concrete hardens increase the likehood that the steel will corrode
- Reactions with the carbon dioxide in the air make the concrete less alkaline and remove the stable iron oxide coating that prevents the orange rust formation
- Infiltration of chlorides from sea spray or road salt increase corrosion
- Hollow spots around the steel expose the metal surface





Increasing the Volume of the Iron Oxide Layer Cracks the Concrete

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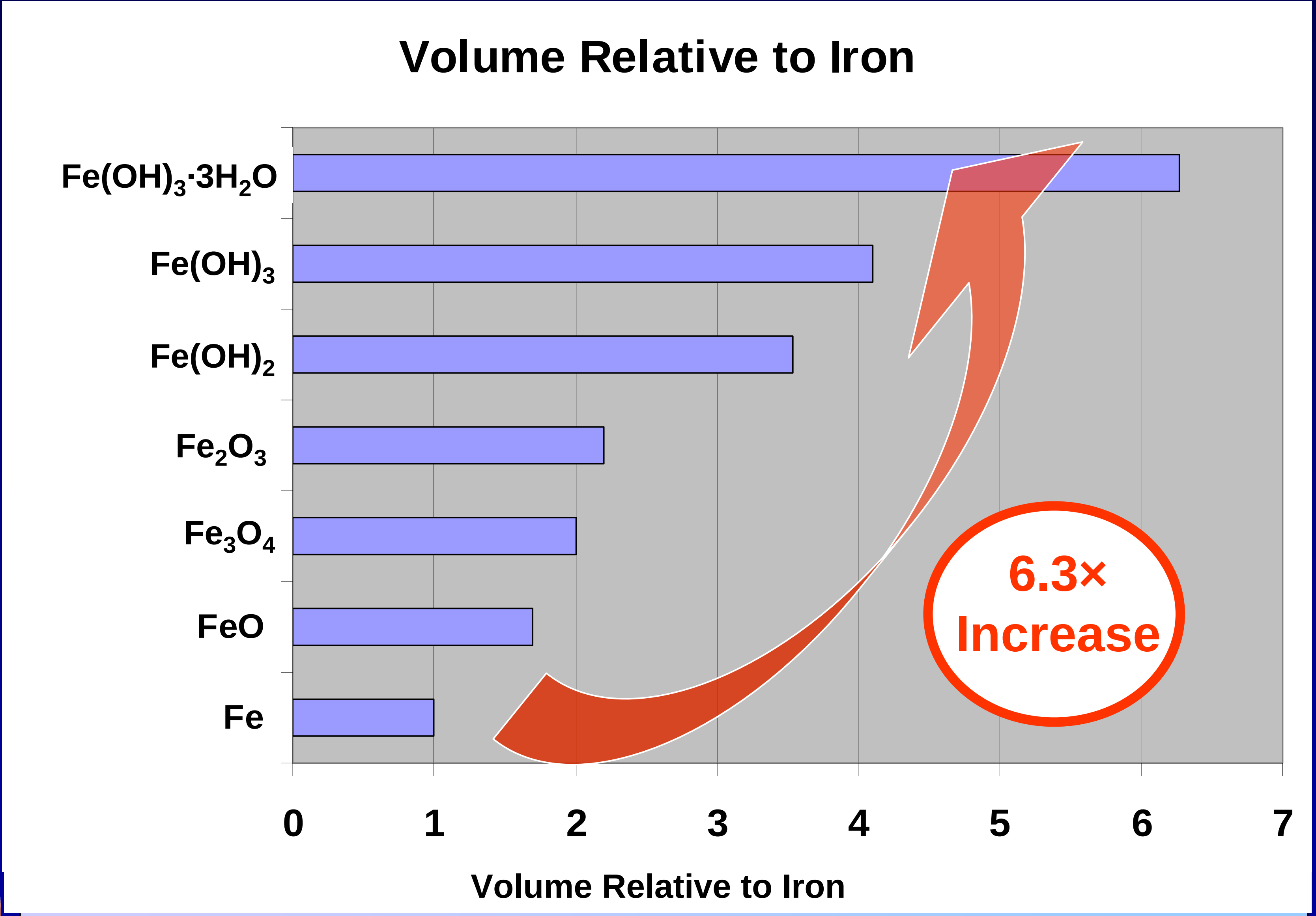

Strategies to Prevent Corrosion

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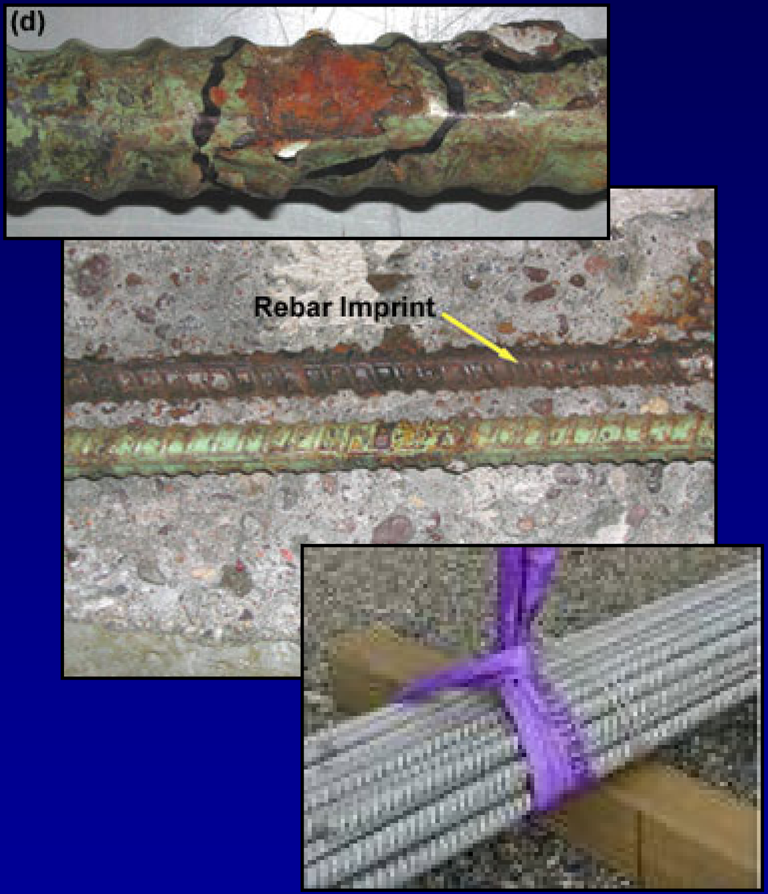
- Coat the reinforcement with an insulator
- Maintain the alkalinity of the surface of the steel reinforcement
- Coat reinforcement with sacrificial metal (zinc)
- Substitute a non-corroding reinforcement materials (stainless steel, fiber-reinforced polymer)
- Add corrosion inhibitors to the concrete
- Use a external cathodic protection system
- Use combinations of systems

All of the above have been tried! There are no economical solutions!

Reinforcement Developed for Stopping Corrosion

- Black steel with organic coatings such as hot fused epoxy
- Black steel with hot-dip galvanizing
- Specialty alloys such as MMFX
- Stainless steel cladding
- Solid stainless steel (316)
- Glass fiber reinforced polymer rebar (FRP)
- Black steel with vitreous enamel coating



How does Bonding Enamel Work?

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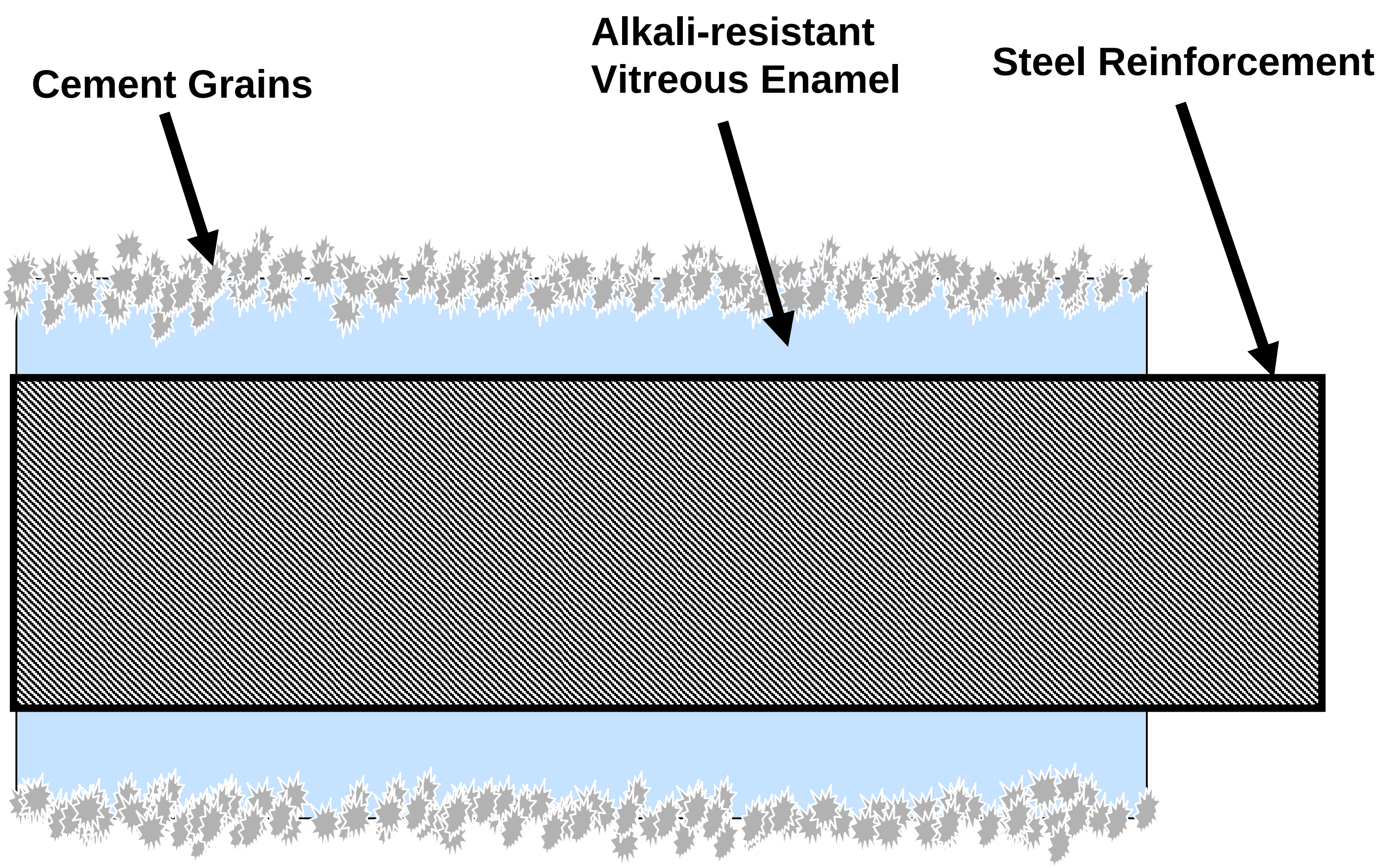

Enamel protects and steel from corrosion; the cement grains hydrate and bond to surrounding concrete

Bonding Enamel Has Serious Advantages!

- Enamel insulates the surface and prevents electrochemical effects that cause corrosion
- Enamel covers the surface to prevent chloride contact
- Provides a tight bond and dense cemented layer

The cement-glass layer fused to the surface of the steel produces a bond strength that is significantly <u>greater</u> than that obtained with a bare steel surface (usually at least 2 to 4 times greater). All other coatings <u>decrease</u> bond strength.

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Enameled Test Rods

- Rods can be single-coated and fired once or double coated and fired twice
- Firing temperatures were in the 745 °C to 850 °C
- Firing times ranged from 2 minutes to 10 minutes

Mild Steel Test Rods

Alkali-resistant Enamel

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COMPOSITION OF CONVENTIONAL AND ALKALI-RESISTANT GROUNDCOAT ENAMELS FOR STEEL				
Constituent	Conventional Groundcoat		Alkali-resistant Groundcoat	
	Amount (%)	Range (%)	Amount (%)	Range (%)
Silicon dioxide SiO_2	54.69	51 – 65	42.02	40 – 45
Boron oxide B_2O_3	12.47	9 – 15	18.41	16 – 20
Na oxide Na_2O	14.77	12 – 15	15.05	15 – 18
K oxide K_2O	1.71	1.7 – 3	2.71	2 – 4
Li oxide Li_2O	nil		1.06	1 – 2
Ca oxide CaO	4.54	3.5 – 5.3	4.47	3 – 5
Aluminum oxide Al_2O_3	8.85	6 – 9	4.38	3 – 5
Zr oxide ZrO_2	**nil**		**5.04**	**4 – 6**
Cu oxide CuO	nil		0.07	nil
Mn dioxide MnO_2	0.45	0.4 – 0.7	1.39	1 – 2
Ni oxide NiO	nil		1.04	1 – 2
Cobalt oxide Co_3O_4	0.31	0.2 – 0.35	0.93	0.5 – 1.5
Phosphorus oxide P_2O_5	nil		0.68	0.5 – 1
Fluorine F_2	2.27	1.7 – 2.6	2.75	2 – 3.5

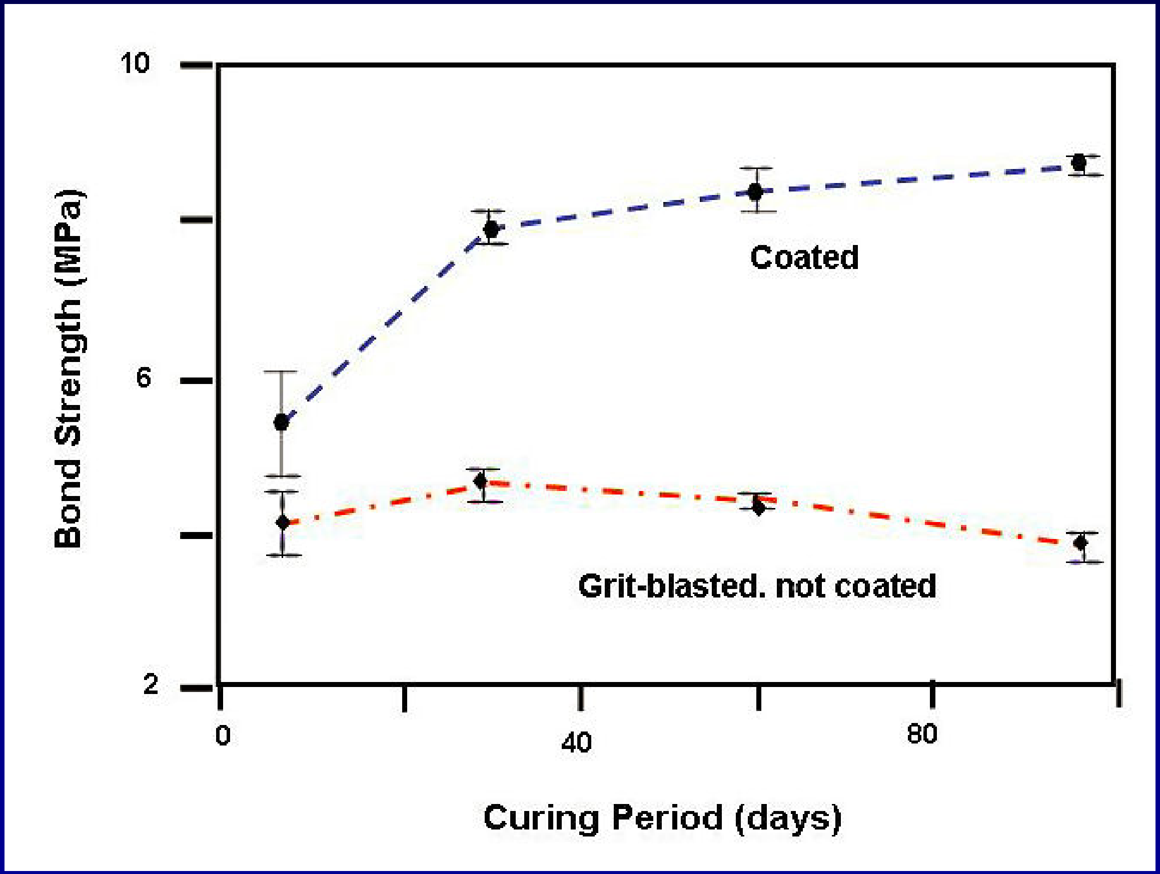
Reactive Enamel Increases Strength

COMPARISON OF AVERAGE BOND STRENGTHS			
Treatment	Average Peak Force (N)	Std. Deviation (N)	Average Bond Strength (MPa)
Steel fiber embedded in mortar	---	---	2.04 – 2.72
Steel rods, uncoated embedded in mortar	2,618.2	466.2	2.06
Enameled rods without portland cement embedded in mortar	3,497.9	540.8	2.70
Rods with enamel containing portland cement embedded in mortar	11,124.6	235.3	8.79

3 or 4× STRONGER BOND

Reactive Enamel Increases Strength Over Time

- **Bond strength of coated rebar increases over time**
- **Bond strength of non-coated rebar lower, and decreases over time**

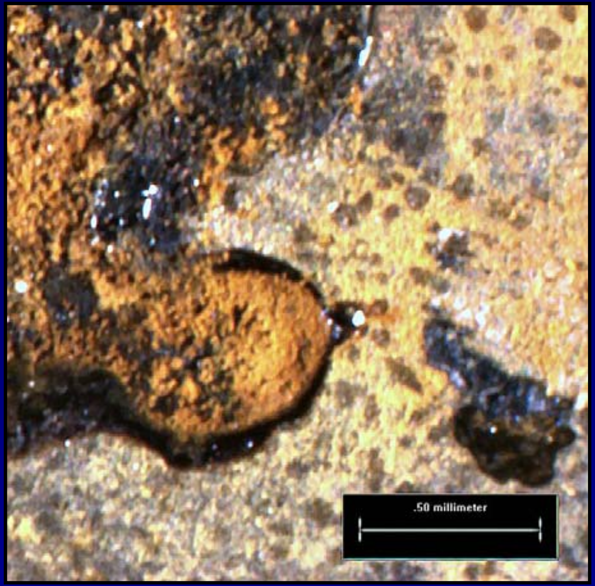


Salt Water Exposure Testing

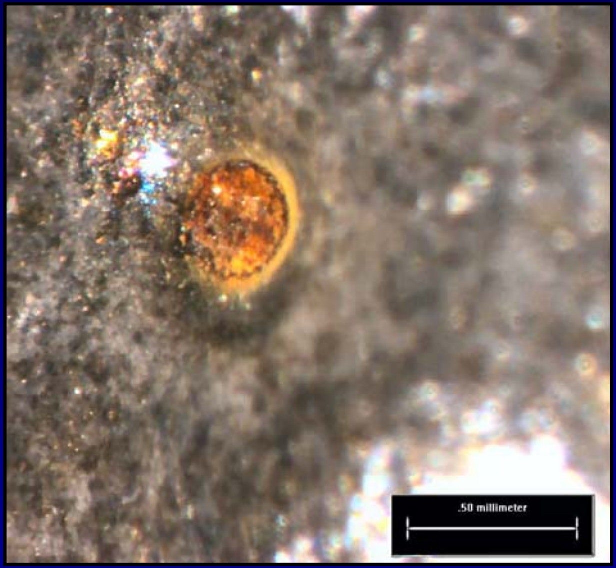
Exposure in Partly Saturated Quartz Sand with 3.5% Sodium Chloride Solution at 20 °C

Salt Water Exposure of Bare Metal and Drilled Enamel

After 72-hour Exposure



Bare metal showed rapid corrosion over full surface



Enamel steel showed corrosion only where a hole had been cut through the enamel

Salt Water Exposure at 40-days for Bare and Coated Test Rods

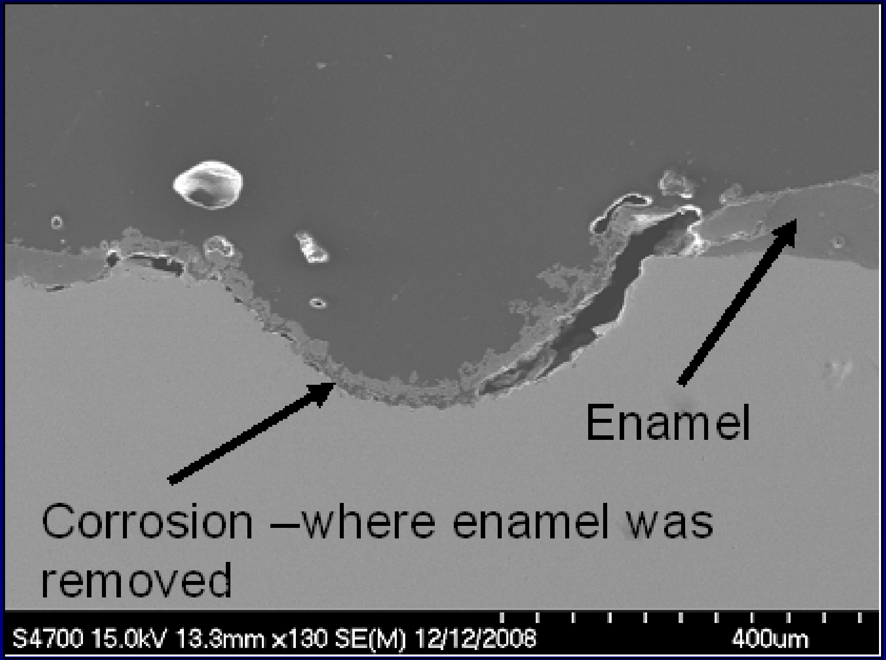
Results of 40-day exposure of mild steel test rods in 3.5% NaCl solution at 20 °C

Alkali-resistant ground coat enamel

Alkali-resistant ground coat enamel w/ portland cement

Cement on surface that contacted water hydrated

Salt Water Exposure at 40-days for Coated Test Rods



- **SEM photomicrograph of the edge of a groove cut in the enamel to expose underlying metal.**
- **Rod was embedded in resin, sliced and polished to show the edges of the bare metal area. The enamel does not debond or allow capillary transfer of salt solutions**

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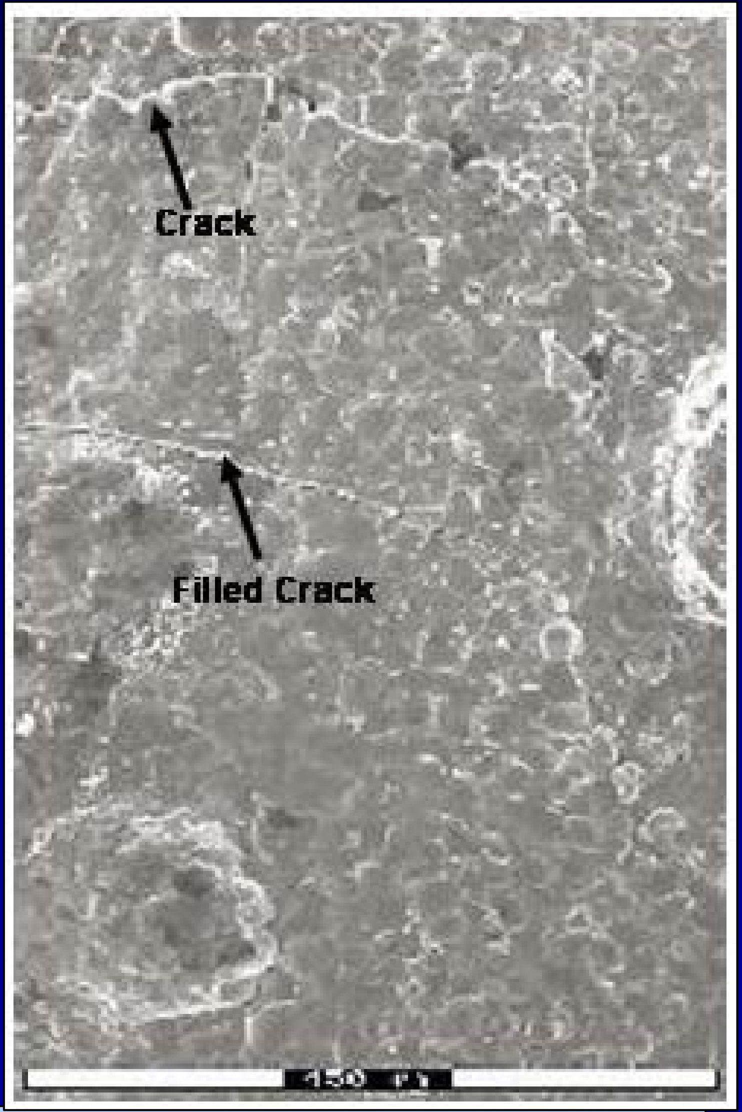
- **SEM Surface of enameled metal wire bent to produce fractures and partly wetted to produce examples of open and filled fractures.**
- **The reacted cement on the surface produces the irregular surface texture.**



CCAD Demonstration
Cooling Tower Support
and Street Section

CCAD Cooling Tower Support

- Exposure to Atmospheric Chlorides from Gulf of Mexico
- Spalling concrete from corroding steel

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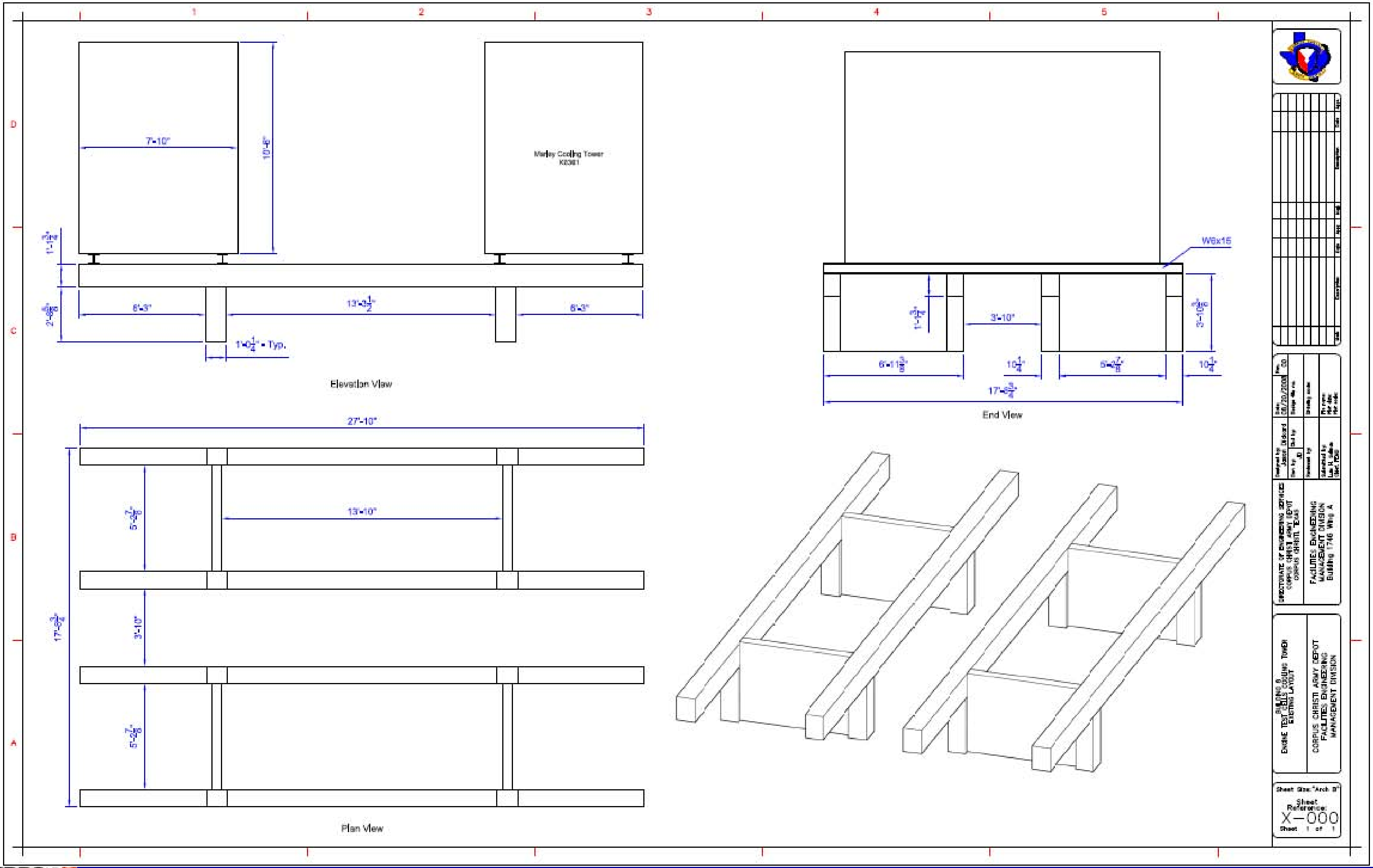
CCAD Cooling Tower Support Beams



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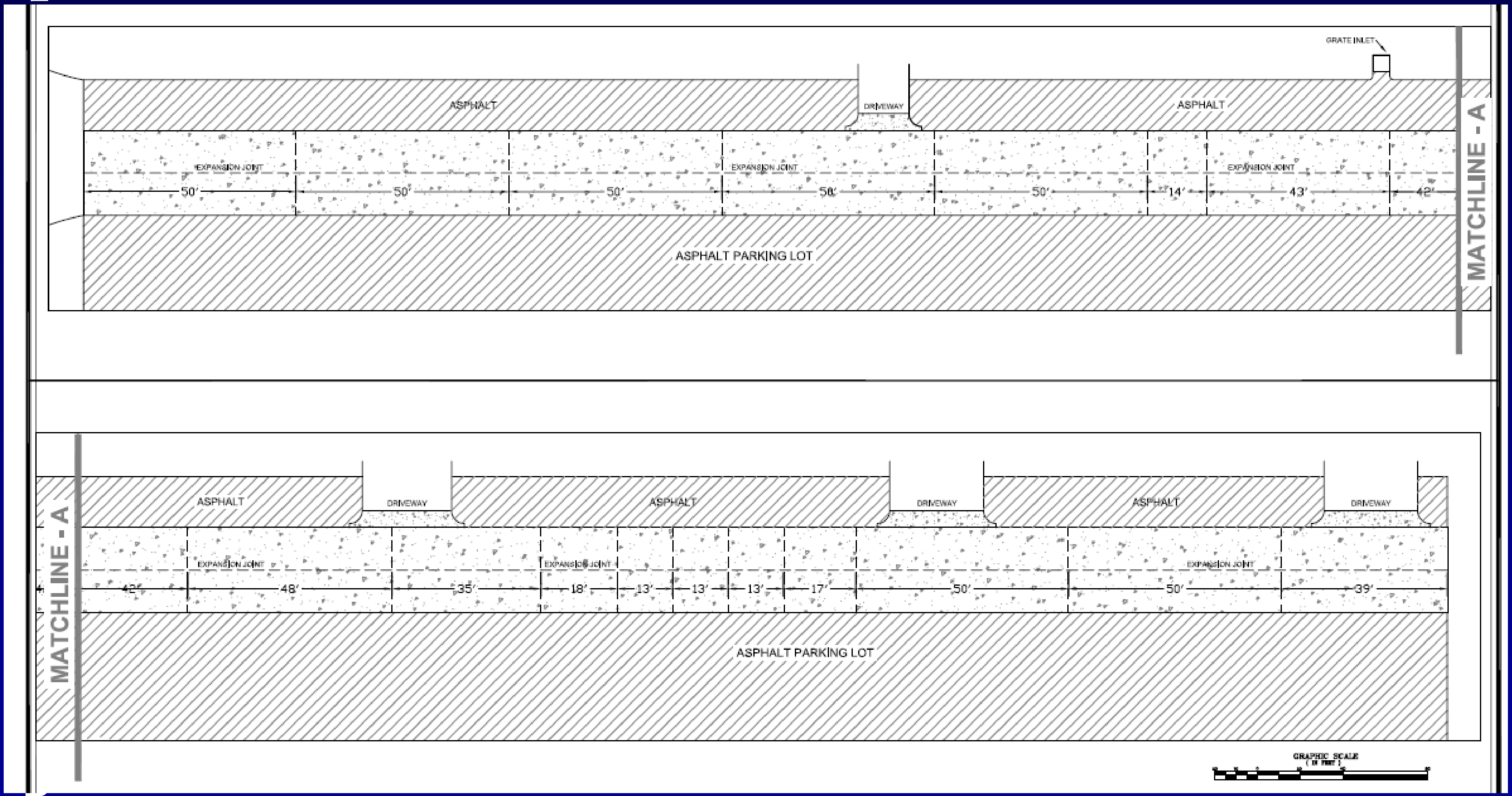
CCAD Street Section



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Summary

- The cement-glass interface produces a bond strength to the steel that is at least 3 to 4 times greater compared to bare steel alone
- The cement-glass enamel hydrates in the same way as conventional cement. Morphological and chemical changes in the cement embedded in the glass is consistent with conventional hydration
- Enameling is very effective in preventing corrosion. In testing corrosion has not been observed on the steel when the enamel is not purposely removed
- Bonding enamel potentially can be very useful in creating reinforced concrete with an improved composite character and improved corrosion resistance
- Work at CCAD will demonstrate the technology on a much larger scale, yielding real world load bearing and corrosion performance data

Bonding Enamel on Reinforcing Steel Has Many Applications

MASONRY ANCHORS AND FITTINGS

- **It can go into pre-cast or cast-in-place concrete**
- **It can be go onto steel decking for concrete floor construction**
- **Masonry anchors and "appliances" that have to bond to mortar can be enameled**

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